Applied Energy 250 (2019) 273–282

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Emission factors of fugitive methane from underground coal mines in China: Estimation and uncertainty

Ke Wang[a], Jianjun Zhang[a,b,*], Bofeng Cai[c], Shengmin Yu[d,*]

[a] School of Land Science and Technology, China University of Geosciences, Beijing 100083, China
[b] Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and Resources, Beijing 100083, China
[c] Center for Climate Change and Environmental Policy, Chinese Academy for Environmental Planning, Beijing 100012, China
[d] National Center for Climate Change Strategy and International Cooperation, Beijing 100038, China

## HIGHLIGHTS

- 10,951 underground coal mines are selected as research samples.
- The national and provincial coal mine methane emission factors are calculated.
- The uncertainty range of different methane emission factors are determined.
- The detailed and updateable emission factor matrices are established.
- Improve the accuracy of China's greenhouse gas emissions inventories.

## ARTICLE INFO

*Keywords:*
Underground coal mine
Methane emission factors
National
Provincial
Uncertainty analysis

## ABSTRACT

Fugitive methane from underground coal mining is the main source of methane emissions in China. Accurate and updateable methane emission factors for underground coal mining are of great significance for the accounting of methane emissions in China. In this paper, 10,951 underground coal mines are investigated for developing an emission factor matrix for national and provincial scales. For national emission factors, 27 types of emission factors are determined according to the classification of the ownership of the enterprise, gas emission rate, and maximum mining depth. For provincial emission factors, three types of emission factors for 25 provinces are determined based on gas emission rates. Based on these metrics, this paper uses bootstrap and Monte Carlo simulations to determine the uncertainty range of different emission factors at the 95% confidence interval (CI). The results show that emission factors at the national scale ranged from 3.005 $m^3/t$ to 54.487 $m^3/t$, with a 95% CI of 2.735 $m^3/t$ to 76.082 $m^3/t$, and that emission factors at the provincial scale ranged from 0.58 $m^3/t$ to 56.19 $m^3/t$, with a 95% CI of 0.347 $m^3/t$ to 108.115 $m^3/t$. By comparison, the emission factors calculated in this paper are more representative than the default values recommended by the Intergovernmental Panel on Climate Change (IPCC). In addition, these results are more specific and updateable than those in previous studies, which lays a foundation for the future study of fugitive methane emissions from underground coal mines at different scales.

## 1. Introduction

Global climate change, especially global warming, is closely linked to human survival and development and exposes human societies and ecosystems to risk. It has become a global consensus that human activities are the culprit of global warming [1]. In addition to paying more attention to reducing $CO_2$ emissions, reducing non-$CO_2$ greenhouse gas emissions is also an important means of mitigating global warming [2]. Non-$CO_2$ greenhouse gases emissions contributed approximately 27% to the total greenhouse gas emissions covered by the Kyoto Protocol in 2010 [3]. Specifically, methane is regarded as the second largest driver of global climate change after $CO_2$, and is one of the six greenhouse gases proposed by the Kyoto Protocol [4]. The global warming potential (GWR) of methane is 25 times that of $CO_2$ over 100 years [5], and concentrations of methane have increased by 150% since 1750 [6]. Therefore, as a major contributor to methane emissions, coal mining

* Corresponding authors at: School of Land Science and Technology, China University of Geosciences, Beijing 100083, China (J. Zhang); National Center for Climate Change Strategy and International Cooperation, Beijing 100038, China (S. Yu).
*E-mail addresses:* zhangjianjun@cugb.edu.cn (J. Zhang), yusm@ncsc.org.cn (S. Yu).

https://doi.org/10.1016/j.apenergy.2019.05.024
Received 22 December 2018; Received in revised form 19 April 2019; Accepted 2 May 2019

activities have naturally attracted widespread attention.

Approximately 45% of the word's coal is produced in China [7], making it a major producer and consumer of coal, and underground coal mines produce more than 90% of raw coal [8]. The underground coal mines in China are mined at deeper depths and have higher gas emission rates, emitting more methane than open-pit coal mining [9]. According to official Chinese statistics, coal mining activity emitted approximately 25,000 Gg of methane in 2012, ranking first in the world and accounting for approximately 45% of total methane emissions in China [10]. This means that the mere consideration of $CO_2$ emissions does not reflect the actuality of the greenhouse gas emissions in China [11]. Fugitive methane emissions from underground coal mining are also an important facet to consider in reducing greenhouse gas emissions in China and must be paid more attention.

In recent years, methane emissions from underground coal mines has been widely investigated by domestic scholars and related organizations. Such studies have mainly been concentrated on two topics– the extraction and utilization of methane in underground coal mines [12] and the calculation of methane emissions from underground coal mines [13]. Regarding the calculation of methane emissions from underground coal mines, the most common calculation scheme was developed by the Intergovernmental Panel on Climate Change (IPCC), which recommends using an emission factor multiplied by the raw coal production as a formula to estimate coal mine methane emissions. Three methods are proposed: Tier 1, Tier 2 and Tier 3 [14]. These three methods have different applicable conditions and emission factors. Tier 1 uses the global average range of emission factors (10–25 $m^3$/t), which is high uncertainty and generally not recommended. Tier 2 recommends countries to calculate country-specific emission factors based on their domestic coal mine characteristics. Tier 2 is less uncertain than Tier 1, which has an uncertainty range of 50%-75%. Tier 3 has the lowest uncertainty and requires measured data from each coal mine in the country to calculate methane emissions from top to bottom.

The differences in emission factors will have a large impact on the accounting of carbon emissions [15]. Thus, an accurate emission factor is critical for calculating methane emissions. In terms of the calculation method of determining the emission factor, most countries with more underground coal mines adopt a method that uses the weighted average of measured data by coal production. These include the USA, India, South Africa, Czech Republic and Poland; among these, there are differences in the classification of emission factors. Specifically, India divides underground coal mines into Degree I, Degree II and Degree III according to the percentage of methane in the general body of air and the rate of methane emission [16]. Poland measures and calculates underground coal mine methane emission factors associated with the ventilation system, degasification system, post-mining processes and goaf [17]. The USA [18], South Africa [19] and Czech Republic [20] do not classify methane emission factors. In addition to the method of weighted average of measured data, it is also a common method to estimate the emission factors of coal mines without measured data by establishing a quantitative relationship between emission factors and coal production for coal mines with measured data [21–24]. Moreover, in countries such as Australia [25], Japan [26] and Slovenia [27], each underground coal mine has an emission factor that corresponds to its domestic coal mine characteristics.

Compared to foreign countries, underground coal mines in China are widely distributed, and due to complicated geological conditions, there are various burial depths and coalbed methane reserves [28], as well as different mining methods, advances in mining technology, and other factors; each underground coal mine has different emission characteristics and these emission factors change dynamically. Therefore, low-accuracy Tier 1 [29] and outdated Tier 2 [30–34] emission factors are not applicable to estimate emissions of coal mine methane in China, which leads to significant differences in the estimates of methane emissions from underground coal mines in China (in which the highest estimate is approximately 5 times higher than the lowest) [35–37]. To compensate for the lack of accuracy in Tier 1 and the shortcomings of the outdated emission factors, some Chinese scholars have paid more attention to the characteristics of coal mines when accounting for methane emissions. Su et al. used available and measurable mine site data, such as coal reserves, ventilation air released, methane concentration and methane release rates, to determine fugitive methane emissions from five underground coal mining areas in China. However, this method is only suitable for studying typical coal mines and cannot obtain universal methane emission factors [38]. Wang et al. used 798 underground coal mines in China as research samples to investigate the relationship between the relative gas emission rate and coal production and proposed a formula to estimate the methane emission factors in underground coal mines. The results showed that the national emission factor is approximately 9.176 $m^3$/t, and the provincial emission factor ranges from 2.697-35.427 $m^3$/t. This approach shows progress in applicability at the regional scale, but due to sample size limitations, the accuracy of such emission factors must be improved [39]. Ju et al. investigated the relationship between the relative gas emissions and in situ gas content of 7 typical coal mines in China and established a new methane emission accounting model based on four parameters including in situ original gas content, gas remaining post desorption, raw coal production, and the mining influence coefficient; this approach considers the gas geology, emission characteristics and existing methods in China. This method is more accurate than Tier 2, but the parameters required for the calculation are not suitable for macro-calculations [40].

In summary, although some scholars and related organizations have studied fugitive methane emissions from underground coal mines, due to sample and data limitations and a paucity of reasonable estimation methods, it is impossible to systematically and accurately investigate actual fugitive methane emissions in China. To correct this, it is important to improve the applicability of emission factors. Moreover, as a large country that is responsible for global greenhouse gas emission reduction work, it is important to establish a more accurate emission factor matrix and accounting system to improve the accounting accuracy of methane emissions. Therefore, this paper applies the data including spatial location information, absolute gas emission rate, coal production, maximum mining depth, and ownership of enterprise from more than 10,000 underground coal mine enterprises, calculating emissions factors at the country and province levels and providing a detailed, localized and updateable emission factor matrix for calculating underground coal mine emissions.

## 2. Materials and methods

### 2.1. Classification of underground coal mine types

Compared to other countries, China has more underground coal mines. Although the United States is the second largest producer of coal in the world, the number of underground coal mines in China is more than 10 times that of the United States [41,42]. The large workload has made it difficult for China to carry out Tier 3 to calculate underground coal mine fugitive methane emissions. Therefore, this paper divides China's underground coal mines based on different classification standards and calculates emission factors of different types of mines. Considering the mainstream classification standards of domestic and international underground coal mines and the practicality of research results, this paper classifies sample coal mines from three perspectives: gas emission rate, ownership of enterprise and maximum mining depth. For the gas emission rate and the ownership of enterprise, the National Coal Mine Safety Administration and the National Energy Administration has issued a method for classifying coal mine gas grades in China [43]. The classification categories based on gas emission rates are listed in Table 1. According to the enterprise ownership of different underground coal mines, the results were divided into three categories: (1) State-owned coal mines, (2) local state-owned mines, and (3) township

**Table 1**
Classification of underground coal mine gas grade.

| | Low gas mine | High gas mine | Gas outburst mine |
|---|---|---|---|
| Relative gas emission | $\leq 10\,m^3/t$ | $> 10\,m^3/t$ | Mines that have experienced gas outbursts or are at risk of potential outbursts |
| Absolute gas emission | $\leq 40\,m^3/min$ | $> 40\,m^3/min$ | |
| Absolute gas emission in the heading face | $\leq 3\ m^3/min$ (each heading face) | $> 3\ m^3/min$ | |
| Absolute gas emission in coal mining face | $\leq 5\ m^3/min$ (each heading face) | $> 5\ m^3/min$ | |

Notes: Low gas mines must meet the four requirements in the table at the same time, while high gas mines only need to meet one of the four requirements.

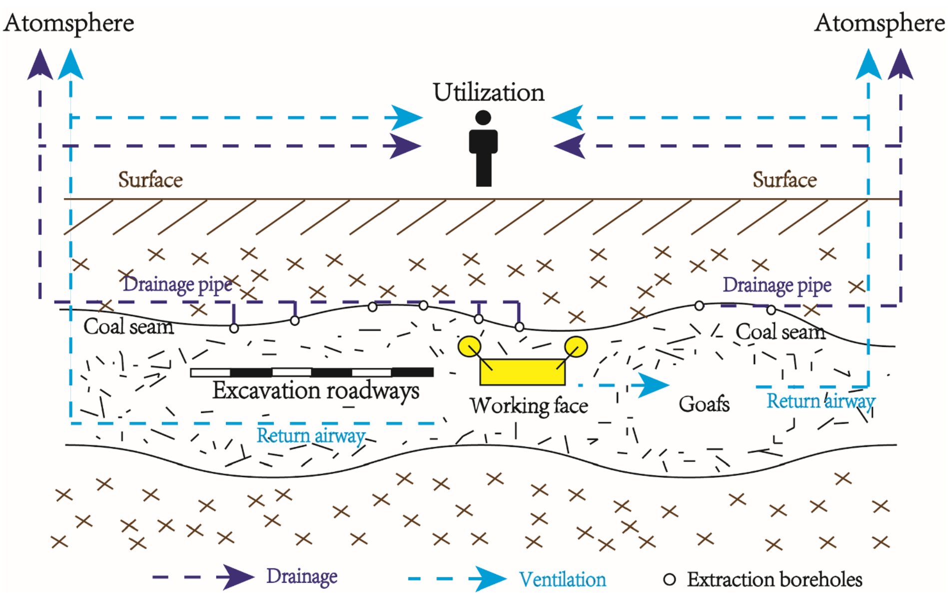



**Fig. 1.** A schematic plan for methane emissions in an underground coal mine. Underground coal mines fugitive methane, which exists in working face, excavation roadways and goafs, is discharged into the atmosphere though return airway (ventilation system) and drainage pipe (degasification system), and some of methane in degasification system are used in human production activities.

coal mines. The classification categories based on maximum mining depth are: (1) greater than 400 m, (2) less than 200 m and (3) between 200 and 400 m, which is divided according to the 2006 IPCC guidelines.

## 2.2. Calculation method of gas emission

(1) Calculation method of absolute gas emission

Underground coal mining generates methane from both ventilation and degasification systems (Fig. 1). Such underground coal mine methane emissions are generally emitted at centralized locations, which are considered as point emission sources [44]. Therefore, they are amenable to standard measurement methods.

The absolute gas emission refers to the total amount of emitted gas per unit of time and takes the largest daily average value among the three measurement days of the identification month. The absolute gas emission is the sum of the gas emission and the extraction volume of the underground coal mine. The amount of gas emission is the difference between the gas flow rate of all inlet and returned air. When there are multiple inlet passages and return air passages in the measurement area, the absolute gas emission amount includes the sum of the gas emissions of all ventilation circuits. The amount of underground gas drainage is the monthly average (including ground and underground drainage). The formula for calculating the absolute gas emission of each ventilation circuit is as follows [43]:

$$q_a = q_{em} + q_{ex} \tag{1}$$

where $q_a$ ($m^3/min$) represents the absolute gas emission in the measurement area; $q_{em}$ ($m^3/min$) represents the daily average gas emissions by wind in the measurement area; and $q_{ex}$ ($m^3/min$) represents the monthly average gas extraction in the measurement area.

$$q_{em} = \frac{1}{n}\sum_{i=1}^{n} q_{emi} = \frac{1}{n}\sum_{i=1}^{n} (Q_{ri}\bullet C_{ri} - Q_{ei}\bullet C_{ei}) \tag{2}$$

where n represents the working shift system, for example, when the coal mine adopts a three-shift system, n = 3; $i$ represents the serial number of the measurement group; $q_{emi}$ ($m^3/min$) represents the emission of ventilation air methane (VAM) in group i; $Q_{ri}$ ($m^3/min$) represents the wind flow in the air return pathway in group $i$ (average of 3 measurements); $C_{ri}$ (%) represents the gas density in the air return pathway in group $i$ (average of 3 measurements); $Q_{ei}$ ($m^3/min$) represents the wind flow in the intake airflow roadway in group $i$ (average of 3 measurements); and$C_{ei}$ (%) represents the gas density in the intake airflow roadway in group i (average of 3 measurements).

(2) Calculation method of relative gas emission

$$q_r = 1440 \times \frac{q_a}{D} \tag{3}$$

where $q_r$ ($m^3/t$) represents the relative gas emission; $q_a$ ($m^3/min$) represents the absolute gas emission; $D$ (t/d) represents the monthly average daily coal production; and 1440 is the number of minutes in a day.

(3) Calculation method of national and provincial scale methane emission factors

$$EF_{national,t} = \frac{1}{n_t}\sum_{i=1}^{n_t} q_{rti} \tag{4}$$

where t represents the type of underground coal mines of interest; i represents the i-th coal mine in the t-type underground coal mine; $q_r$ ($m^3/t$) represents the relative gas emission; $EF_{national,t}$ ($m^3/t$) represents the national methane emission factor of t-type underground coal mines; $n_t$ represents the number of t-type underground coal mines; and $q_{rti}$

($m^3/t$) represents the relative gas emission from the i-th coal mine in t-type underground coal mines;

$$EF_{provincial,p,t} = \frac{1}{n_{pt}} \sum_{i=1}^{n_{pt}} q_{rpti} \tag{5}$$

where p represents the province; $q_r$ ($m^3/t$) represents the relative gas emission; $EF_{provincial,p,t}$ ($m^3/t$) represents the provincial methane emission factor of the t-type underground coal mines in p province; $n_{pt}$ represents the number of t-type underground coal mines in p province; and $q_{rpti}$ ($m^3/t$) represents the relative gas emission from the i-th coal mine of the t-th type coal mine in the p province.

### 2.3. Uncertainty analysis method

The AuvTool is an analysis tool that enables an analyst to quantify variability in a dataset and to quantify uncertainty in key statistics of the dataset. The software was developed specifically to support the Stochastic Human Exposure and Dose Simulation (SHEDS) model that is being developed by the U.S. Environmental Protection Agency (EPA) [45]. The AuvTool was used to quantitatively determine underground coal mine emission factors of each type classified in this paper. The matrix matching method (MoMM) was used to estimate and fit each parameter, and seven different distribution functions were used (Table 2). MoMM is based on matching the moments or central moments of a parametric distribution (e.g., mean, variance) to the moments or central moments of the data set. This method is often the most straightforward to implement. Therefore, it typically satisfies the criterion of practicality [46]. Synthetic datasets of the same sample sizes as the original datasets were then generated from the assumed probability distribution using random Monte Carlo sampling. This sampling was conducted 2,000 times for each parameter. The Kolmogorov–Smirnov (K-S) parameter was selected to test the optimal probability distribution model, and finally, the uncertainty range of each type's emission factor was determined at a 95% confidence interval (CI). The design concept of the AuvTool software is shown in Fig. 2.

**Table 2**
Definitions of Parametric Probability Distributions.

| Name of distribution | Probability density function |
|---|---|
| Normal | $f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$ |
| Lognormal | $f(x) = \begin{cases} \frac{1}{x\sqrt{2\pi}\sigma} e^{\frac{-(lnx-\mu)^2}{2\sigma^2}}, (x > 0) \\ 0, (x \le 0) \end{cases}$ |
| Beta | $f(x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha,\beta)}(0 \le x \le 1)$ |
| Gamma | $f(x) = \frac{\beta^{\alpha}x^{\alpha-1}e^{-\beta x}}{\Gamma(\alpha)}(x > 0)$ |
| Weibull | $f(x) = \frac{c}{k}(\frac{x}{k})^{c-1}e^{\left[-\left((\frac{x}{k})^c\right)\right]}(x > 0)$ |
| Uniform | $f(x) = \frac{1}{b-a}(a \le x \le b)$ |
| Symmetric Triangle | $f(x) = \frac{b-\lvert x-a\rvert}{b^2}(a-b \le x \le a+b)$ |

Notes: For Normal distribution and Lognormal distribution, $\mu$ is the arithmetic mean, $\sigma$ is the arithmetic standard deviation. For Beta distribution, $\alpha$ and $\beta$ are shape parameters, and $B(\alpha, \beta)$ is the Beta function. For Gamma distribution, $\alpha$ is the shape parameter, $\beta$ is the scale parameter, and $\Gamma(\alpha)$ is the Gamma function. For Weibull distribution, $k$ is the scale parameter, and $c$ is the shape parameter. For the uniform distribution, $a$ and $b$ are the lower and upper limits of the variable. For the symmetric triangle distributions, $a$ and $b$ determine the range of variables.

### 2.4. Data sources and geographical distribution

#### 2.4.1. Data sources

The underground coal mine spatial location data were derived from the CHRED (China High Resolution Emission Gridded Database), established by the Environmental Planning Institute of the Ministry of Ecology and Environment, which is constructed based on bottom-up enterprise-level data. This database, including more than 1.5 million industrial enterprises, is sourced from the national pollution source census and regular pollution reporting systems in China [48]. The CHRED covers almost all point sources of carbon emissions in China, even many small-scale enterprises. Therefore, this database can be widely used to spatially analyze underground coal mine methane emissions in China.

The underground coal mine gas emission rate, ownership of enterprise, maximum mining depth, and coal production data from the 2011 national coal mine gas classification are identified in the compilation. Coal production data from provincial statistical yearbooks and the China Coal Industry Statistical Yearbook are used to correct the coal production parameters in sample coal mines.

#### 2.4.2. Underground coal mine spatial distribution

From the perspective of the spatial distribution of underground coal mines in China, they are mainly distributed in Shanxi, Yunnan, Sichuan, Guizhou, Hunan and Sichuan. In addition to the Shanxi Province, other large mining provinces are mainly concentrated in the south part of China. The numbers of underground coal mines in Qinghai, Tibet and the eastern coastal provinces are generally lower (Fig. 3).

There are obvious differences in the types of underground coal mines in China (Fig. 3). From the perspective of ownership of enterprises, township coal mines are the main type of underground coal mine, which account for approximately 76% of the total. These coal mines are mainly distributed in the central and western provinces of the Yangtze River, such as Sichuan, Yunnan, Hunan, and Chongqing. State-owned coal mines account for approximately 13% of the total, which are mainly distributed in the central provinces north of the Yangtze River, such as Shanxi and Henan. Local state-owned coal mines are mainly distributed in Shanxi, Shandong and Xinjiang, accounting for only 11% of all underground coal mines (Fig. 4(a)).

From the perspective of gas emission rate, the number of low gas mines is the largest, accounting for approximately 73% of all underground coal mines, mainly located in Sichuan, Yunnan, Shanxi, Hunan, and Chongqing. These are also the provinces that contain more high gas mines. It is worth noting that there are more high gas mines in Guizhou, second only to Sichuan. Gas outburst mines are mainly distributed in Hunan and Guizhou (Fig. 4(b)).

From the perspective of maximum mining depth, due to data limitations, more than half of underground coal mines cannot provide maximum mining depth data, but the spatial analysis only includes coal mines with reported maximum mining depths. The number of underground coal mines with maximum mining depths of 200–400 m is the largest, accounting for more than 40% of the total. Coal mines with a maximum mining depth greater than 400 m account for approximately 30%, which also reflects the increasing depth of underground coal mines in China. Coal mines with maximum mining depths of 200–400 m are mainly concentrated in Chongqing, Shanxi, Sichuan and Heilongjiang, and those with maximum mining depths of more than 400 m are mainly located in Shanxi, Sichuan and Henan. It is worth noting that nearly 50% of underground coal mines in the eastern provinces have maximum depths of more than 400 m, which is mainly related to the geological conditions and coal reserves [49]. Coal mines with maximum mining depths of less than 200 are interspersed among several large coal-producing provinces, accounting for 29% of all coal mines (Fig. 4(c)).

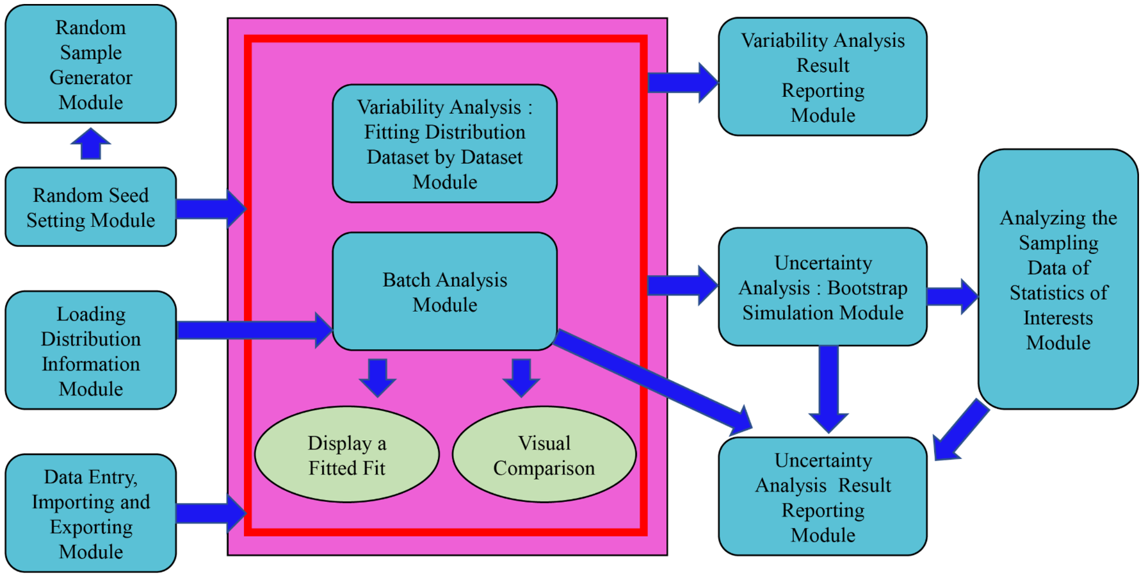



**Fig. 2.** Conceptual Structural Design of the AuvTool System [47]. The AuvTool is composed of different modules. The data import/export module, random sampling module and result reporting module are the basic module of the AuvTool. The core module are the variability and uncertainty analysis module, which has the ability to simulate the optimal probability distribution and uncertainty range of sample datasets.

## 3. Results and analysis

### 3.1. Methane emission factors at the national scale and uncertainly analysis

This study selects underground coal mines that can provide ownership of enterprise, gas emission rate, maximum mining depth and gas emission data; there are 4011 underground coal mines that can provide such information. According to the three classification criteria of the ownership of enterprise, gas emission rate and maximum mining depth, these underground coal mines were divided into $3 \times 3 \times 3 = 27$ types of emission factor matrices.

In this paper, the uncertainly of the emission factor is mainly composed of the uncertainties related to measurements and statistical calculations. The former is difficult to quantify and can only be qualitatively analyzed, whereas the latter can quantitatively estimate the uncertainty of each emission factor using the uncertainty analysis method. Therefore, based on bootstrap simulations, the emission factor uncertainty range in the statistical calculations and its optimal statistical distribution of different types of emission factors in the 95% CI are determined (Table 3). Due to the article length limit, only three examples of probability distribution bands are shown in Fig. 5 for state-owned low gas mines with different maximum depths.

It is apparent that the average methane emission factors of different types of township coal mines are generally higher than those of local state-owned and state-owned coal mines. In local state-owned coal mines, the average emission factors of gas outburst coal mines with

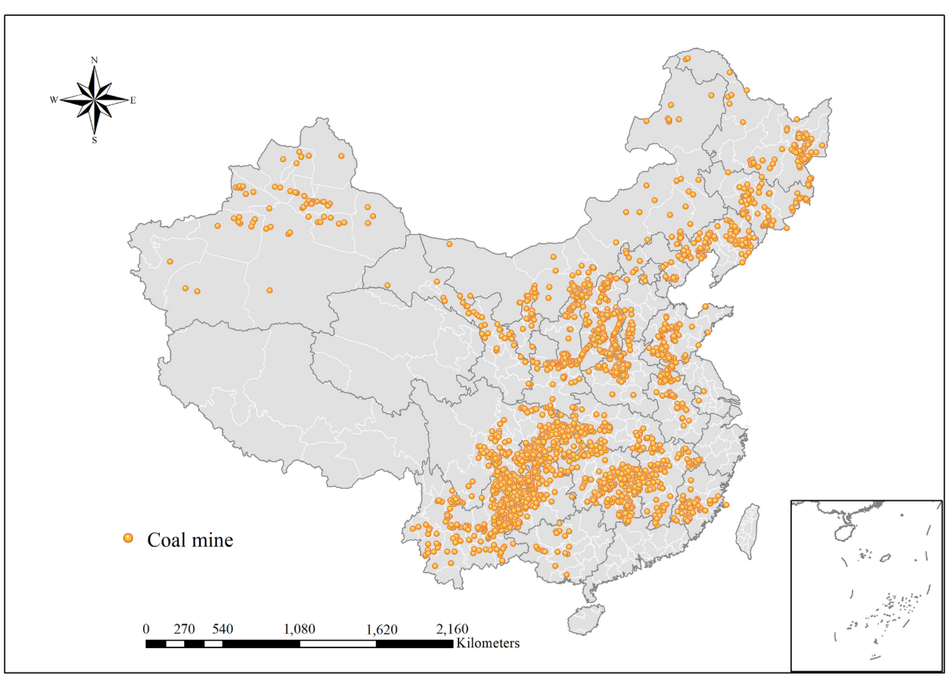
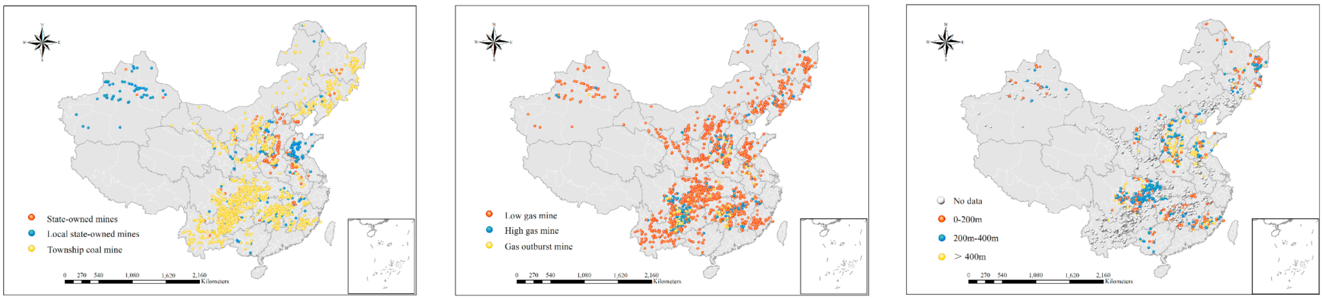



**Fig. 3.** Spatial distribution of underground coal mines in China. 1,0951 underground coal mines are distributed in 25 provinces in China (there are no underground coal mines in Tianjin, Shanghai, Guangdong, Hainan, Qinghai, Tibet and Taiwan), and underground coal mines in the south are more densely distributed.




(a) Ownership of enterprises (b) Gas emission rate (c) Maximum mining depth

**Fig. 4.** Spatial distributions of different types of underground coal mines in China. The figure shows the spatial heterogeneity and aggregation of different types of underground coal mines.

different mining depths are highest in the entire emission factor matrix. From the uncertainty analysis, the optimal statistical distribution of most coal mine types is a lognormal distribution, accounting for one-third of the total. The coal mines with Weibull distributions are second only to the lognormal distributions. Only the gas outburst mines with depths of 200–400 m in the local state-owned coal mines present a normal distribution (see Table 4).

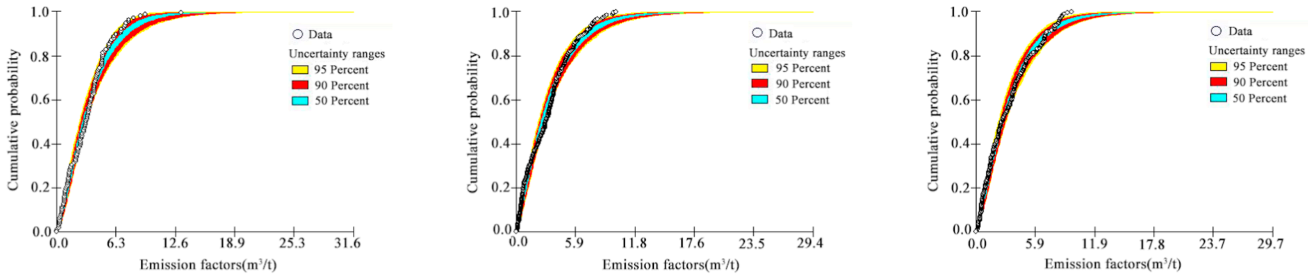
### *3.2. Methane emission factors at the provincial scale and uncertainly analysis*

In the provincial research, due to the limitations of sample data (some provinces did not report data for coal mine maximum depths), this paper only discusses emission factors of different provinces from the perspective of gas emission rates. However, because of the variation in burial depth of coal seams in the province [49], this provincial emission factor matrix still has high precision and application significance. From the comparison of methane emission factors in provincial underground coal mines, it is apparent that there are similarities and differences in the spatial distribution of the three types of underground coal mines (Fig. 6). The similarity lies in the fact that no matter what kind of gas-type coal mines are considered, those in Yunnan, Sichuan, Chongqing, Hunan and Hubei have higher emission factors, and those in eastern coastal provinces (Shandong and Jiangsu) generally have lower emission factors. The difference is that the emission factors in low gas mines show more significant spatial agglomeration and spatial heterogeneity. The provinces with high emission factors are concentrated along the southern part of the Yangtze River, whereas those with low emission factors are concentrated along the north part of the Yangtze River. The spatial agglomeration and heterogeneity of the high gas mines and gas outburst mines are not significant. For high gas mines, high emission factors are located in southern and northeastern provinces (e.g., Heilongjiang). For gas outburst mines, provinces with high emission factors occur both in southern (Sichuan, Chongqing, Guizhou) and northern (Ningxia, Shanxi, Liaoning) provinces. From the uncertainty analysis, the optimal distribution of most types of coal mines is Weibull, which account for 34% of the total (Table 5). Coal mine types with a lognormal distribution account for 27% of the total, and only a few coal mine types show a normal distribution.

**Table 3**
Underground coal mine methane emission factors at the national scale.

| Ownership of enterprise | Gas emission rate | Maximum depth of mining (m) | Sample number | The average of relative gas emission ($m^3/t$) | Optimal distribution | 95% CI uncertainty range ($m^3/t$) |
|---|---|---|---|---|---|---|
| State owned coal mine | Low gas mine | D < 200 | 120 | 3.324 | Weibull | 2.918–3.766 |
| | | 200 ≤ D ≤ 400 | 274 | 3.174 | Weibull | 2.924–3.552 |
| | | D > 400 | 241 | 3.270 | Weibull | 2.966–3.669 |
| | High gas mine | D < 200 | 7 | 12.253 | Weibull | 8.989–15.797 |
| | | 200 ≤ D ≤ 400 | 53 | 16.823 | Lognormal | 13.649–20.542 |
| | | D > 400 | 99 | 23.065 | Lognormal | 19.549–27.291 |
| | Gas outburst mine | D < 200 | 3 | 12.340 | Gamma | 6.728–22.336 |
| | | 200 ≤ D ≤ 400 | 24 | 45.330 | Weibull | 32.646–66.809 |
| | | D > 400 | 129 | 27.420 | Lognormal | 22.544–32.958 |
| Local state-owned coal mine | Low gas mine | D < 200 | 170 | 3.588 | Gamma | 3.208–4.003 |
| | | 200 ≤ D ≤ 400 | 204 | 3.716 | Gamma | 3.407–4.089 |
| | | D > 400 | 177 | 3.005 | Gamma | 2.735–3.338 |
| | High gas mine | D < 200 | 9 | 15.857 | Gamma | 12.005–20.314 |
| | | 200 ≤ D ≤ 400 | 37 | 28.355 | Lognormal | 21.204–36.202 |
| | | D > 400 | 36 | 24.200 | Gamma | 19.279–28.875 |
| | Gas outburst mine | D < 200 | 3 | 54.487 | Gamma | 32.212–76.082 |
| | | 200 ≤ D ≤ 400 | 12 | 43.443 | Normal | 33.622–52.070 |
| | | D > 400 | 11 | 35.241 | Weibull | 21.236–49.483 |
| Township coal mine | Low gas mine | D < 200 | 624 | 4.980 | Normal | 4.738–5.258 |
| | | 200 ≤ D ≤ 400 | 845 | 5.720 | Weibull | 5.652–6.176 |
| | | D > 400 | 323 | 5.070 | Weibull | 4.882–5.443 |
| | High gas mine | D < 200 | 129 | 25.450 | Lognormal | 22.727–28.817 |
| | | 200 ≤ D ≤ 400 | 169 | 28.660 | Lognormal | 25.418–31.593 |
| | | D > 400 | 111 | 26.573 | Lognormal | 23.983–29.390 |
| | Gas outburst mine | D < 200 | 93 | 31.250 | Lognormal | 28.842–33.651 |
| | | 200 ≤ D ≤ 400 | 72 | 35.460 | Lognormal | 31.452–39.922 |
| | | D > 400 | 36 | 32.011 | Gamma | 27.442–36.713 |

Notes: D represents the maximum depth of mining.

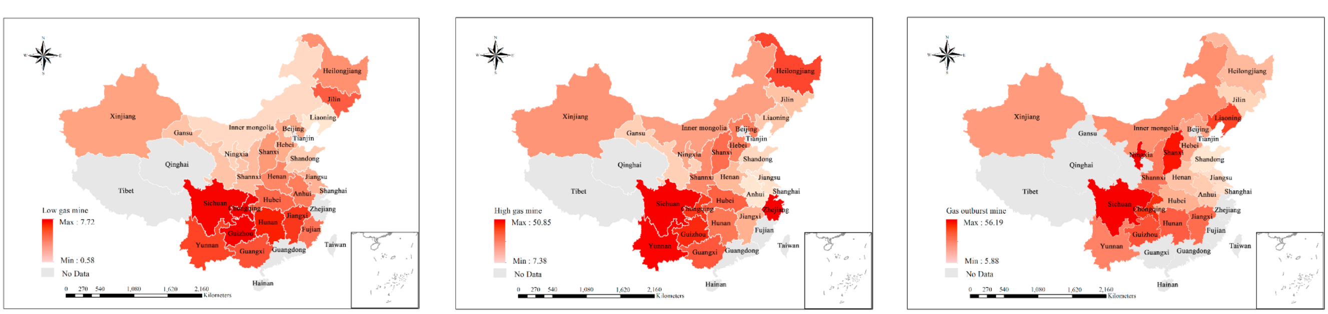



(a) State owned - low gas - <200 m (b) State owned - low gas - 200–400 m (c) State owned - low gas - >400 m

**Fig. 5.** Probability distribution bands of emission factors of three types of coal mines. Within the 50%, 90% and 95% uncertainty range, the optimal probability distribution of fugitive methane emission factors in different types of underground coal mines are simulated.

**Table 4**
Underground coal mine methane emission factors at the provincial scale.

| Province | Low gas mine | | High gas mine | | Gas outburst mine | |
|---|---|---|---|---|---|---|
| | Sample number | The average of relative gas emission ($m^3$/t) | Sample number | The average of relative gas emission ($m^3$/t) | Sample number | The average of relative gas emission ($m^3$/t) |
| Beijing | 4 | 1.433 | – | – | – | – |
| Hebei | 50 | 2.914 | 14 | 17.812 | 7 | 17.524 |
| Shanxi | 574 | 3.423 | 167 | 22.653 | 29 | 46.398 |
| Inner Mongolia | 244 | 1.451 | 10 | 16.918 | 3 | 25.200 |
| Liaoning | 373 | 0.584 | 39 | 12.318 | 16 | 40.588 |
| Jilin | 172 | 5.465 | 29 | 12.679 | 1 | 12.380 |
| Heilongjiang | 515 | 3.529 | 45 | 23.655 | 8 | 14.890 |
| Jiangsu | 18 | 2.789 | 1 | 9.060 | 2 | 7.955 |
| Zhejiang | – | – | 1 | 50.850 | – | – |
| Anhui | 56 | 3.869 | 13 | 7.381 | 34 | 13.721 |
| Fujian | 203 | 4.155 | – | – | – | – |
| Jiangxi | 204 | 6.089 | 106 | 14.765 | 16 | 31.122 |
| Shandong | 182 | 1.931 | 3 | 12.203 | 2 | 5.880 |
| Henan | 318 | 3.441 | 27 | 12.136 | 68 | 14.569 |
| Hubei | 257 | 5.057 | 17 | 22.066 | 14 | 16.544 |
| Hunan | 537 | 6.435 | 143 | 20.272 | 264 | 32.635 |
| Guangxi | 35 | 5.516 | 2 | 22.115 | – | – |
| Chongqing | 447 | 7.080 | 107 | 30.431 | 78 | 41.812 |
| Sichuan | 257 | 6.923 | 188 | 33.656 | 44 | 44.289 |
| Guizhou | 165 | 7.665 | 240 | 30.129 | 207 | 37.562 |
| Yunnan | 722 | 6.077 | 132 | 32.559 | 69 | 29.569 |
| Shaanxi | 300 | 2.457 | 13 | 17.842 | 5 | 32.130 |
| Gansu | 132 | 2.418 | 3 | 12.250 | – | – |
| Ningxia | 26 | 1.615 | 2 | 15.215 | 3 | 56.187 |
| Xinjiang | 139 | 3.024 | 10 | 17.008 | 1 | 25.140 |




(a) Low gas mine (b) High gas mine (c) Gas outburst mine

**Fig. 6.** Spatial distribution of methane emission factors at the provincial scale. The figure shows the inter-provincial spatial characteristics of different types of emission factors (The shade of red represents the size of the emission factor, i.e., the darker the color, the larger the emission factor, and the gray represents the province without data).

**Table 5**
Uncertainty of methane emission factors in underground coal mines.

| Province | Low gas mine | | High gas mine | | Gas outburst mine | |
|---|---|---|---|---|---|---|
| | Optimal Distribution | 95% CI uncertainty range ($m^3/t$) | Optimal Distribution | 95% CI uncertainty range ($m^3/t$) | Optimal distribution | 95% CI uncertainty range ($m^3/t$) |
| Beijing | Weibull | 0.806–2.362 | – | – | – | – |
| Hebei | Weibull | 2.323–3.585 | Lognormal | 8.789–30.627 | Normal | 12.207–21.935 |
| Shanxi | Gamma | 3.211–3.645 | Gamma | 21.119–24.887 | Weibull | 35.914–55.309 |
| Inner Mongolia | Lognormal | 1.289–1.687 | Lognormal | 11.066–24.504 | Weibull | 13.569–38.240 |
| Liaoning | Lognormal | 0.429–0.842 | Weibull | 6.500–14.113 | Weibull | 21.779–79.246 |
| Jilin | Normal | 5.089–5.758 | Normal | 11.110–14.356 | – | – |
| Heilongjiang | Normal | 3.294–3.771 | Lognormal | 19.867–27.956 | Gamma | 8.448–21.553 |
| Jiangsu | Normal | 1.960–3.893 | – | – | – | – |
| Zhejiang | – | – | – | – | – | – |
| Anhui | Gamma | 3.475–4.294 | Gamma | 5.877–9.408 | Lognormal | 10.705–17.920 |
| Fujian | Weibull | 3.880–4.342 | – | – | – | – |
| Jiangxi | Normal | 5.812–6.359 | Weibull | 13.934–15.612 | Normal | 25.699–36.657 |
| Shandong | Gamma | 1.748–2.178 | Gamma | 9.340–16.122 | – | – |
| Henan | Normal | 3.239–3.719 | Gamma | 9.709–15.115 | Weibull | 13.188–17.606 |
| Hubei | Weibull | 4.772–5.279 | Lognormal | 17.707–26.983 | Gamma | 11.920–22.193 |
| Hunan | Weibull | 6.271–6.632 | Lognormal | 18.588–22.038 | Lognormal | 30.810–34.942 |
| Guangxi | Normal | 4.754–6.435 | – | – | – | – |
| Chongqing | Weibull | 6.724–7.140 | Lognormal | 25.962–34.586 | Lognormal | 34.028–48.409 |
| Sichuan | Weibull | 6.510–7.227 | Lognormal | 30.909–35.876 | Lognormal | 37.338–51.213 |
| Guizhou | Normal | 7.352–7.933 | Lognormal | 27.951–32.901 | Gamma | 34.942–40.480 |
| Yunnan | Weibull | 5.965–6.212 | Lognormal | 29.261–36.187 | Gamma | 24.921–34.977 |
| Shaanxi | Weibull | 2.228–2.686 | Lognormal | 11.170–27.323 | Gamma | 23.240–41.423 |
| Gansu | Weibull | 2.212–2.569 | Weibull | 10.464–13.776 | – | – |
| Ningxia | Weibull | 0.905–2.165 | – | – | Weibull | 24.561–108.115 |
| Xinjiang | Gamma | 2.717–3.297 | Lognormal | 12.965–22.239 | – | – |

## 4. Discussion and conclusions

### 4.1. Main achievements

The absolute methane emissions from 10,951 underground coal mines in China were measured and classified to obtain national- and provincial-level emission factors. These emission factors (relative methane emissions), which are presented by a matrix of factors, are measured according to the absolute gas emission and coal production of different types of coal mines.

For national emission factors, China's underground coal mines are divided into 27 categories from three perspectives including ownership of enterprise, gas emission rate and maximum mining depth, from which the emission factors for different types of underground coal mines are calculated. Among the 27 types, the minimum emission factor is 3.005 $m^3/t$ with a 95% CI of 2.735–3.338 $m^3/t$; the maximum emission factor is 54.487 $m^3/t$ with a 95% CI of 32.212–76.082 $m^3/t$. By contrast, the emission factor in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories is 10–25 $m^3/t$. This shows that the reference value of the emission factor given by the IPCC does not truly reflect the true value of various types of underground coal mines in China, and the deviation is relatively large.

For provincial emission factors, there are significant spatial differences including significant variation between provinces. The provinces with high emission factors are generally concentrated in the central and western regions south of the Yangtze River, and the highest value is nearly two orders of magnitude higher than the lowest value. The emission factor of low gas mines in Liaoning is the smallest, only 0.584 $m^3/t$ with a 95% CI of 0.429–0.842 $m^3/t$. The highest emission factor is associated with gas outburst mines in Ningxia, reaching 56.187 $m^3/t$ with a 95% CI of 24.561–108.115 $m^3/t$. Comparing national and provincial emission factors, the range of emission factors from the provincial scale is larger than the range of emission factors at the national scale, which indicates that as the scale of research attains higher resolution, emission factors will become more precise.

The originality of this paper is to propose the multi-dimensional emission factor matrix and its uncertainty of fugitive methane in underground coal mines at the national and provincial scales, and compared to previous studies, this paper has more underground coal mine samples and more detailed classification [22,50]. Therefore, whether it is accounting for underground coal mine methane emissions from national, provincial or municipal scales, the accuracy is higher in comparison.

### 4.2. Limitations and uncertainties

The measurement data for methane emissions from underground coal mines are from 2011, but they are more updateable and comprehensive than data used in other research, as these are the latest data from China. Moreover, due to differences in available sample size caused by different underground coal mine classification types at the two scales of studies, there is a small difference between the weighted provincial emission factors and the national emission factors, but the provincial weighted factor is within uncertainty at the 95% CI of the national factor, and the gap is controlled within 0.3 $m^3/t$. Therefore, it is reasonable to use the 2011 data to update and supplement the current methane emission factors of underground coal mines at the national and provincial scales. In addition to improving monitoring systems and updating data, more accurate emission factors can be expected in the future.

In the classification of the emission factor matrix at the national scale, due to the limitation of data statistics, the maximum depth of mining is used as the classification standard, rather than average depth of mining. In this paper, the correlation between the maximum depth of mines and the relative emission of methane is analyzed. According to the verification analysis, underground coal mines with maximum mining depths less than 200 m have an average methane emission factor of 9.27 $m^3/t$. The average emission factor for mines with maximum depths from 200 to 400 m is 10.30 $m^3/t$, and the average emission factor for mines with maximum mining depths greater than 400 m is 12.16 $m^3/t$. The validation results are consistent with those in the IPCC report, in which underground coal mines with the highest maximum mining depths often have higher methane emissions. Therefore, it is appropriate to classify according to the maximum mining depth.

The emission factor matrix established in this study cannot be self-

tested. This paper can only be verified against existing reports, such as the IPCC report and other scientific literature.

### 4.3. Implications and applications

Whether domestic or international, accounting for greenhouse gas emissions is continuously updated every year, and the contribution of high-precision and updateable emission factors to greenhouse gas accounting is unobjectionable. Therefore, the research results of this paper have important and widely applicable significance, both domestically and abroad.

For domestic applications, emission factors at different scales can provide scientific support for the preparation of China's national greenhouse gas emission inventories and can provincial greenhouse gas emission inventories. With regard to detailed and accurate national emission factors, it is helpful to accurately calculate the methane emissions of underground coal mines in China and thus lay a foundation for China to better formulate national greenhouse gas emission reduction plans and fulfill global carbon emission reduction responsibilities. With regard to provincial methane emission factors, it is possible to calculate China's methane emissions from underground coal mines by using bottom-up methods and thus calculate methane emissions at the provincial/municipal scale. The provincial emission factors also help to accurately identify high emission areas and thus help decision makers in developing emission reduction options from smaller administrative units, thereby improving the accuracy of the carbon emission accounting system in China's carbon market.

Internationally, the emission factors can provide more accurate basic parameters for the compilation of international greenhouse gas emission inventories and associated methods, as well as for the construction of a global climate change prediction model. The research ideas in this paper can provide a reference for building emission factor matrices in other countries, especially countries with a large number of underground coal mines. The construction method of the hierarchical emission factor matrix at different scales can improve the accuracy of methane emission in underground coal mines in various countries and can also facilitate more accurate horizontal comparisons between countries, provinces and cities around the world to clarify each country's responsibility toward emission reductions. Furthermore, accurate emission factors play an important role in the international carbon trading market, which can further improve the accuracy of the international carbon accounting system and gain each country more voice in climate negotiations.

## Acknowledgments

This article is funded by the Fundamental Research Funds for the Central Universities (Grant Number: 2652018042). Thanks to all reviewers for their valuable advice on this paper.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.05.024.

## References


[1] Liu H, Rodríguez G. Human activities and global warming: a cointegration analysis ☆. Environ Modell Software 2005;20:761–73.
[2] Lucas PL, van Vuuren DP, Olivier JG, Den Elzen MG. Long-term reduction potential of non-$CO_2$ greenhouse gases. Environ Sci Policy 2007;10:85–103.
[3] Grubb M, Vrolijk C, Brack D. The Kyoto Protocol. A guide and assessment. Mol Ecol 1999;13:2121–33.
[4] Landman W. Climate change 2007: the physical science basis. South African Geogr J Being A Record Proc South African Geogr Soc 2007;92:86–7.
[5] Solomon S. IPCC (2007): climate change the physical science basis. Am Geophys Union 2007;9:123–4.
[6] Pachauri RK, Meyer LA, Team CW. IPCC, 2014: Climate Change 2014: Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. J Romance Stud 2014;4:85–8.
[7] Birol F. Key world energy statistics. Int Energy Agency 2017.
[8] Yuan BR, Nie ZR, Xiang-Hua DI, Zuo TY. Life cycle inventories of fossil fuels in China(I): Energy sources consumption and direct pollutant emissions. Modern Chem Indus 2006;26:59–61.
[9] Cheng Y-P, Wang L, Zhang X-L. Environmental impact of coal mine methane emissions and responding strategies in China. Int J Greenhouse Gas Control 2011;5:157–66.
[10] The People's Republic of China. The First Biannual Updated Report on Climate Change; 2016.
[11] Zhang B, Chen G, Li J, Tao L. Methane emissions of energy activities in China 1980–2007. Renew Sustain Energy Rev 2014;29:11–21.
[12] Zhou F, Xia T, Wang X, Zhang Y, Sun Y, Liu J. Recent developments in coal mine methane extraction and utilization in China: A review. J Nat Gas Sci Eng 2016;31:437–58.
[13] Kirchgessner DA, Piccot SD, Winkler JD. Estimate of global methane emissions from coal mines. Chemosphere 1993;26:453–72.
[14] Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K. 2006 IPCC guidelines for national greenhouse gas inventories: Institute for Global Environmental Strategies Hayama, Japan; 2006.
[15] Zhu L, Dabo G, Wei W, Davis SJ, Philippe C, Jin B, et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 2015;524:335–8.
[16] Singh AK, Kumar J. Fugitive methane emissions from indian coal mining and handling activities: estimates, mitigation and opportunities for its utilization to generate clean energy ☆. Energy Procedia 2016;90:336–48.
[17] Patyńska R. Methodology of estimation of methane emissions from coal mines in Poland. Studia Geotechnica Et Mechanica 2014;36:89–101.
[18] EPA. Inventory of US greenhouse gas emissions and sinks: 1990-2016; 2018.
[19] Republic of South Africa. GHG NATIONAL INVENTORY REPORT SOUTH AFRICA 2000-2010; 2014.
[20] Czech Republic. National Greenhouse Gas Inventory Report of the Czech Republic (reported inventories 1990- 2015); 2017.
[21] Kirchgessner DA, Piccot SD, Masemore SS. An improved inventory of methane emissions from coal mining in the United States. Air Repair 2000;50:1904–19.
[22] Wang N, Zhu T, Chen S, Luo DW. Study on the interprovincial emission factor of Chinese coal mine methane. Appl Mech Mater 2013;295–298:3354–8.
[23] Li X, Zhang W, Li Y, Wang N, Ren Y. CMM utilization and emission reduction based on gush factor analysis. J China Coal Soc 2014;39(S2):390–6.
[24] Lunarzewski LW. Gas emission prediction and recovery in underground coal mines. Int J Coal Geol 1998;35:117–45.
[25] Australia. National Inventory Report 2015 Volume 1; 2017.
[26] Ministry of the Environment (Japan). National Greenhouse Gas Inventory Report of JAPAN; 2017.
[27] Republic of Slovenia. Slovenia's National Inventory Report 2017; 2017.
[28] Bibler CJ, Marshall JS, Pilcher RC. Status of worldwide coal mine methane emissions and use. Int J Coal Geol 1998;35:283–310.
[29] Wang HL, Wu YF, Fan M, Jiang ZM, Xie YS, Shi JM. Study on methane fugitive emissions from coal mining and handling of Jiangxi Province. Jiangxi Sci 2013;31:321–6.
[30] Ye J, Tang S. Coalbed methane resources of China. China Coalbed Methane 1998:25–8.
[31] Yu S, Wei YM, Guo H, Ding L. Carbon emission coefficient measurement of the coal-to-power energy chain in China. Appl Energy 2014;114:290–300.
[32] Zhang B, Yang TR, Chen B, Sun XD. China's regional $CH_4$ emissions: Characteristics, interregional transfer and mitigation policies. Appl Energy 2016;184:1184–95.
[33] NDRC. The People's Republic of China National Greenhouse Gas Inventory 2005; 2014.
[34] NDRC. The People's Republic of China National Greenhouse Gas Inventory 2008; 2014.
[35] Yang M. Climate change and energy policies, coal and coalmine methane in China. Energy Policy 2009;37:2858–69.
[36] EPA. Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030; 2011.
[37] The People's Republic of China. The Second National Communication on Climate Change; 2012.
[38] Su S, Han J, Wu J, Li H, Worrall R, Guo H, et al. Fugitive coal mine methane emissions at five mining areas in China. Atmos Environ 2011;45:2220–32.
[39] Wang N, Wen Z, Zhu T. An estimation of regional emission intensity of coal mine methane based on coefficient-intensity factor methodology using China as a case study. Greenhouse Gases Sci Technol 2015;5:437–48.
[40] Ju Y, Sun Y, Sa Z, Pan J, Wang J, Hou Q, et al. A new approach to estimate fugitive methane emissions from coal mining in China. Sci Total Environ 2016;543:514–23.
[41] Wang L, Cheng Y-P, Liu H-Y. An analysis of fatal gas accidents in Chinese coal mines. Saf Sci 2014;62:107–13.
[42] Safety M. Health Administration. Approval & Certification Center; 2011.

[43] SAWS. Specification for Identification of Classification of Gassy Mines; 2006.
[44] National Academies of Sciences, Engineering, and Medicine. Improving characterization of anthropogenic methane emissions in the United States: National Academies Press; 2018.
[45] Zheng J, Frey HC. Guiding Principles for Monte Carlo Analysis AuvTool User's Guide. Prepared by North Carolina State University for the US Environmental Protection Agency, Research Triangle Park, NC; 2000.
[46] Shapiro Samuel S. Statistical models in engineering. Wiley 1967.
[47] Frey HC, Zheng J, Zhao Y, Li S, Zhu Y. Technical Documentation of the AuvTool Software Tool for Analysis of Variability and Uncertainty. Prepared by North Carolina State University for the US Environmental Protection Agency, Research Triangle Park, NC; 2000.
[48] Cai B, Liang S, Zhou J, Wang J, Cao L, Qu S, et al. China high resolution emission database (CHRED) with point emission sources, gridded emission data, and supplementary socioeconomic data. Resour Conserv Recycl 2018;129:232–9.
[49] Mao J, Xu H. Chinas coal resource distribution and perspective prediction. Coal Geol Exploration 1999.
[50] Zheng S, Wang Y, Wang Z. China's coal mine methane emissions to the atmosphere. Coal Mine Saf 2005;36:29–33.